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Identifying and Modelling Permit Trucks for Bridge Loading

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Identifying and Modelling Permit Trucks For Bridge Loading

Accurate estimates of characteristic traffic load effects are essential in order to optimize bridge safety assessment. Permit trucks dominate the extreme upper tail of the truck loading distribution and as a result need careful examination. This paper proposes rules for filtering these trucks from Weigh-In-Motion data for both the US and Europe. The importance of these trucks in critical bridge loading events is then examined for both regions. A Monte Carlo traffic simulation model is developed which focuses on the accurate simulation of permit trucks.

Keywords: bridges; traffic engineering; mathematical modelling.

1. Introduction

The truck traffic crossing a highway bridge may be categorized into two types of trucks; standard trucks and permit trucks. Permit trucks exceed the normally allowable weights and/or dimensions and therefore would be expected to have a special permit to use the roads. The extreme loading events likely to cause characteristic (i.e., probable lifetime maximum) load effects on short to medium span bridges are dominated by these very heavy trucks (Enright & OBrien, 2013). The accurate estimation of these load effects is critically important for bridge safety assessment and design. The most accurate method to obtain information on the actual traffic loads on a bridge is to use Weigh-In-Motion (WIM) data (COST323 2002). This is the process of weighing vehicles as they pass along a road a normal highway speeds.

Traffic load models are used in the design and assessment of highway bridges. The models aim to represent the characteristic loading on the bridge and are most accurate if calibrated using WIM data. Bridge design codes treat standard and permit trucks in different ways. Eurocode 1 (EC1 2003) has one load model for standard trucks (Load Model 1) and another (Load Model 3) for permit trucks. These load models can be adjusted for each country based on local traffic. The bridge design code used in the United States (AASHTO 2012) specifies a load model which applies to normal vehicular use of the bridge. This includes all legal trucks, illegal overloads and un-analysed permits (all routine permits) but not special permit trucks, which are required to be individually analysed (Sivakumar et al. 2008). Accurate load models are then not just dependent on the availability of WIM data but also on the ability to identify standard and permit trucks in the WIM data.

The weights of permit and standard trucks are regulated in different ways. Standard truck weights depend on the degree to which legal limits are enforced. Permit trucks, on the other hand, are controlled by the permit issuing authority and are typically subject to stricter regulation and monitoring (Luskin et al. 2000; Koniditsiotis et al. 2012). Permits are usually issued subject to the use of escort vehicles which can reduce the loading on bridges by controlling the position of other traffic travelling in the same direction as the permit truck, but it is difficult for permit-issuing authorities to control the traffic travelling in the opposite direction, which the permit truck might meet as it crosses a bridge. Recent WIM data (Enright & OBrien 2010) has shown that permit trucks occur quite frequently, on a daily or even hourly basis at some sites, and travel alongside regular traffic, sometimes without escort vehicles.

It is generally considered that a truck would not be given a permit if it posed a threat to a bridge but research in the US has found that bridge load effects caused by permit trucks regularly exceed the maximum effects expected by the permitting authority (Zhao & Tabatabai 2012). Moses (2001) gives the example of a 250 tonne truck that illegally travelled over 160 km in Ohio before being stopped by authorities. This indicates that it is not safe to assume that bridge load effects caused by permit trucks will always be within the limits set by the permitting authority, and that a probabilistic analysis is required. The separation of permit and standard trucks when examining bridge loading would allow each vehicle type to be analysed independently in a manner which is appropriate to the level of enforcement and regulation of each truck type in that region.

Whilst WIM systems record many truck characteristics, including individual axle weights, inter-axle spacings, gross vehicle weight (GVW), speed and time of arrival, they do not include any indication of the permit status of the vehicle, and it is not therefore feasible to link the records maintained by permit-issuing authorities with the trucks recorded in the WIM data. Currently no accurate methods exist to identify permit trucks in WIM data. When examining bridge loading on short to medium span bridges, most authors (Nowak 1993; Bailey & Bez 1999; Enright & OBrien 2013) make no distinction between permit and standard trucks. Enright and OBrien (2010) examine permit truck loading on bridges but assume that all extremely heavy trucks have permits, without attempting to differentiate between illegally overloaded standard trucks and permit trucks. A National Cooperative Highway Research Program (NCHRP) report which examines the use of US WIM data for bridge design (Sivakumar et al. 2008) concludes that an approach which uses a state's weight regulations is best.

In this paper, filtering rules are developed which identify the permit trucks in WIM data. The rules are based on legal limits in each country, and on a detailed analysis of extensive WIM databases. The truck population is considered to consist of two types of truck – "apparent standard" and "apparent permit". Both truck types are identified based on their axle layout, rather than on their weights, as trucks of either type may be illegally overloaded. It is acknowledged that the apparent standard trucks may contain trucks with the axle configuration of a standard truck but which have applied for a permit to carry increased weight, and similarly, that the apparent permit trucks may contain trucks which have failed to apply for a permit and are travelling illegally. Nevertheless, it is clear that this approach classifies the truck population into two groups with distinctly different statistical properties. It should be noted that this study only addresses permit trucks which are allowed to travel freely with other traffic and permit trucks with particular requirements, such as the elimination of other traffic, are beyond the scope of this work.

This paper also examines an approach for modelling traffic loading on bridges and, in particular, focuses on the accurate modelling of permit trucks. Different approaches can be used to estimate characteristic load effects from WIM data. Many authors have used statistical extrapolation (Caprani & OBrien, 2010; Cremona, 2001; Nowak & Szerszen, 1998; O'Connor & Eichinger, 2007; O'Connor & OBrien, 2005) or notional load models (Getachew & OBrien, 2007; Miao & Chan, 2002). A potential shortfall of these methods is that it is difficult to ensure that following and meeting events which did not occur during the WIM measuring period are being considered by the extrapolation procedure. Long run simulations can overcome these shortfalls by simulating hundreds or thousands of site-years of traffic which has the same characteristics as the traffic in the WIM measurements. Loading events from the simulation can then be analysed to calculate the characteristic load effects. This approach is used here and a method for simulating permit trucks using simplified axle layouts is developed.

2. Identifying Permit Trucks in WIM Data

To examine apparent permit trucks separately from apparent standard trucks they must first be identified in the WIM data for both Europe and the US.

2.1 WIM data

Five European WIM sites are used in this study. The sites are in the Netherlands, Czech Republic, Poland, Slovakia and Sweden and contain a total of 2.7 million truck records. At these sites, measurements are generally taken in two lanes in one direction. A more detailed description of most of these sites can be found in Enright and OBrien (2012). The US WIM data is from 19 sites in 17 states and contains 81.6 million truck records. At all US sites the data is for the slow lane in one direction of a carriageway with two lanes in each direction. This US data has been gathered as part of a follow-on project of the Federal Highway Administration's Long Term Pavement Performance (LTPP) program for traffic data collection (Walker et al. 2012; Walker & Cebon 2012).

2.2 Truck types

Examination of the WIM data in both regions has shown that permit trucks differ in their weight and axle configuration. Apparent permit trucks in Europe can be categorized into three types, referred to here as low loaders, mobile cranes and trucks carrying crane ballast. These three permit types are identified by examining the axle configuration of the heaviest trucks at the three sites by inspecting photographs of trucks which are available for the Netherlands WIM site (see Figure 1), and using axle configuration plots such as those in Figure 2. "Low loaders" consist of a tractor and trailer and have one large inter-axle spacing, usually 8 – 13 m.

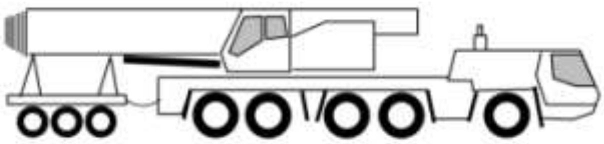
"Mobile cranes" have a rigid body and consist of closely spaced axles with relatively large axle loads. "Crane ballast trucks" consist of a tractor and trailer units but do not have the large spacing that is found on low loaders. They tend to have one slightly larger spacing between the tractor and trailer unit. Both these truck types have a large load concentrated over closely-spaced axles.

In the US data three apparent permit types are also found, low loaders, mobile cranes and mobile cranes with dollies – see Figure 1. The crane ballast trucks which were found in Europe are not found in the US – as crane ballast is divisible it is assumed that it is spread between multiple smaller trucks rather than being carried all on one truck. The mobile cranes in the US generally have fewer axles than Europe and in some cases rest the boom on a trailing dolly to allow the crane's weight to be spread over a greater length. This appears to be in an effort to comply with the federal bridge formula (Jacob et al. 2010) or other local loading rules. This trend in the US, of using axle configurations which distribute the gross vehicle weight over greater truck lengths, is also evident in low loaders in the US – see Figure 2 (a) and 2 (b). The figures show two low loaders of similar weight and with a similar maximum spacing but the US low loader has an additional axle and the axles are spread over a wheelbase that is over one and a half times that of the European low loader. Similar examples are found throughout the WIM data.

(a) Mobile crane (109 tonnes, 9 axles).

(b) Low loader (127 tonnes, 11 axles).

(c) Crane ballast truck (109 tonnes, 10 axles).



(d) Outline drawing of five-axle mobile crane with three-axle dolly.

Figure 1. Photographic evidence of the permit truck types from a Netherlands WIM site (except (d)).

2.3 Legal limits and filtering

Many general vehicle classification schemes exist (COST 323, 2002; FHWA, 2005) but they do not make the distinction between standard and permit trucks. Other bridge assessment guidelines separate permit trucks into different classes (Highways Agency, 2011; O'Connor & Enevoldsen 2009) but they do not specify how permit trucks might be identified in WIM records. An NCHRP (Sivakumar et al. 2008) report makes the simplifying assumption that all trucks in the WIM data with more than six axles have special permits and that all other vehicles are routine permits or legal trucks. This report does however acknowledge that this approach misclassifies long combination vehicles (LCVs) (Schulman 2003), specialized haulage vehicles (Sivakumar et al. 2008) and trucks with grandfathered rights (USDOT 2000) and concludes that an approach which uses a state's weight regulations is best. The term "grandfathered rights" refers to state-specific truck configurations which exceed current regulations but which are exempt in that state as they were legally permitted before the current regulations were introduced.

As a result of the lack of a well-established approach, it is necessary to develop rules to identify permit trucks in the WIM data. Maximum permissible weights and dimensions across Europe (Ceuster et al. 2008) are shown in Table 1, and the regulations are very similar throughout Europe. The notable exception which affects this study is in the Netherlands and Sweden where European Modular System (EMS) trucks are allowed on a trial basis (Akerman & Jonsson 2007). These trucks can have up to nine axles and can be up to 25.25 m long. This information must be incorporated in the rules for distinguishing between standard and permit trucks as EMS vehicles are classified here as standard.

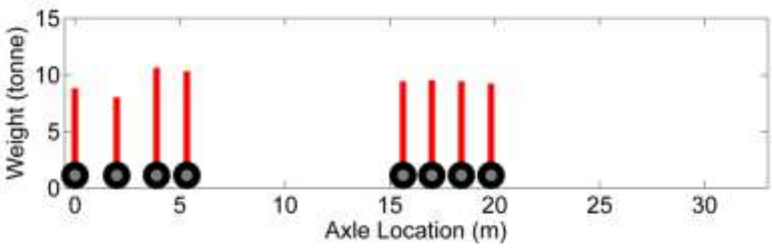
Table 1. European permissible vehicle dimensions

	Maximum Length (m)		
	Rigid Truck	Road Train[a]	Articulated Vehicle[b]
Czech Republic	12	18.75	16.5
Netherlands	12	18.75	25.25[c]
Slovakia	12	18.75	16.5
Sweden	24	24.0	25.25[c]
Great Britain	12	18.75	16.5

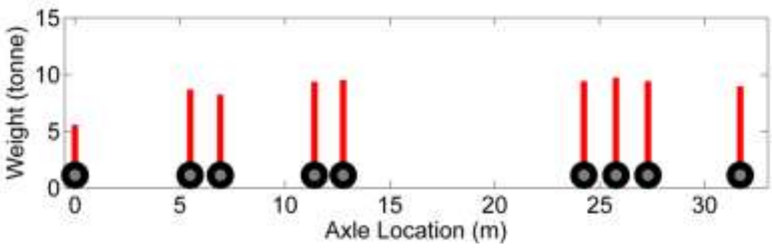
Notes: [a] Truck and trailer(s) combination.
[b] Tractor and trailer (multiple trailers in the case of European Modular System (EMS) vehicles).
[c] EMS vehicles allowed in this country.

In the US the focus of truck restrictions is on weight rather than dimension. Federal truck weight laws apply on the interstate system and limit the GVW to 36.3 tonnes (80,000 pounds) and require all trucks – excluding those with permits or grandfathered rights – to comply with the bridge formula. These restriction do not apply to the other highways within a state but most states adopt these rules (USDOT 2000). Federal law states that trailers in a tractor-semitrailer configuration must not be restricted to a length shorter than 14.6 m (48 ft) on the national network. Many states allow trailers longer than this, up to a maximum of 18.3 m (60 ft) in Wyoming

The rules presented here for both regions are based on the legal requirements (Table 1), a review of the relevant literature, examination of the WIM data at all sites, and on the photographic evidence available from the site in the Netherlands. The rules separate the truck population into "apparent permits" and "apparent standards". The rules are somewhat subjective, but a visual inspection of selected axle configurations (as in Figure 2) suggests that the rules are effective in identifying the two truck categories. It must be noted that gross weight is not used as a criterion so as to avoid incorrectly classifying illegally overloaded standard trucks as permit trucks.



(a) European low loader, with 8 axles and weighing 75 tonnes (permit).



(b) US low loader, with 9 axles and weighing 79 tonnes (permit).

Figure 2. Axle configuration of low loaders measured in the European and US WIM data.

A vehicle is classified as a low loader if it satisfies any of the following rules:

(1) Has more than nine axles.
   (a) In Europe nine axles is the maximum for EMS vehicles and in the US it is the maximum for long combination vehicles (LCVs).
(2) Has the profile of a standard articulated truck, but is longer than the legal limit.
   (a) Standard articulated trucks have one large spacing with more closely spaced axles before and after. This rule does not pick LCVs or EMS trucks as they do not have a single large spacing.
   (b) In the US there is no overall length limit for standard articulated trucks, however, there is a limit on the trailer length. This length is estimated and the truck is selected if the trailer exceeds the maximum allowed.
(3) Has a large truck length and group of four or more axles at back.
   (a) In Europe, a large truck length is defined as greater than length limit for standard articulated trucks (16.5 m).
   (b) In the US it is defined as greater than 20 m as the there is no restriction on overall length of these trucks.
(4) Has an overall length greater than 25.25 m (Europe only).
   (a) This is the maximum legal length in Europe - see table 1.
(5) Has more than six axles with a group of three or more axles at back (US only).
   (a) LCVs do not generally have tridems.

A vehicle is classified as a crane type if it has more than two axles, a maximum spacing less than 4.5 m and an average spacing less than 2.5 m

(1) 3- and 4-axle trucks are chosen only if their average axle weight is over 8 tonnes, to avoid choosing standard trucks with short wheelbases
(2) For Europe, if the maximum spacing is between 3.5 m and 4.5 m, and/or the vehicle has a light first axle (less than 90% of the average axle weight), the vehicle is classified as a crane ballast truck. Crane ballast trucks have lighter front axles, possibly due to this being the steer axle on the tractor unit whereas mobile cranes have heavier front axles, which is thought to be due to the boom extending beyond the front axle.
(3) For the US, trucks with more than five axles, a maximum spacing less than 7 m and an average spacing less than 3 m are also selected and classified as mobile cranes with dollies (MCWD).
(4) For the US, vehicles with closely-spaced semi-trailer configurations are excluded from the crane-type group, as are any vehicles with an average axle weight less than 6 tonnes.

Figure 3 shows the maximum daily GVW's for both apparent standard and apparent permit trucks, after the filter has been applied to a WIM site from both regions – the Netherlands and Arizona. The daily maximum values are plotted on Gumbel probability paper (Ang & Tang 2007) which effectively shows the cumulative distribution function for the data with the y-axis plotted on a double log scale. As the y-axis value increases the probability of occurrence decreases. The double log scale is useful for examining the behaviour of the data in the tail region and examining the appropriateness of the fitted statistical distributions which extrapolate beyond the limits of the data. It can be seen in the figure that the Netherlands site has significantly heavier maximum daily trucks than the Arizona site. It is also seen that the filters succeed in identifying two truck groups with distinctly different statistical properties, which is a key aim of this study.

To compare the characteristic values of both truck types the apparent standards are extrapolated to the 75- and 1000-year return period level. It is a policy decision as to whether apparent permits should be extrapolated in this way but the full extrapolation is shown here for illustrative purposes. At both sites it can be seen that the permit trucks are critical for bridge loading.

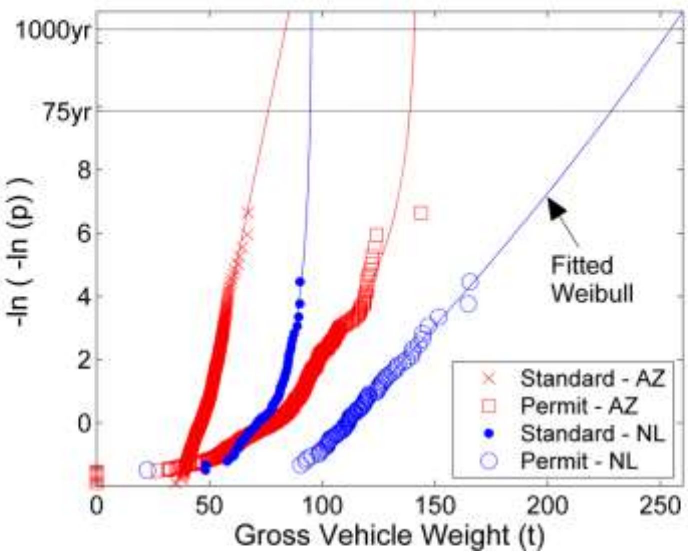


Figure 3. Gumbel probability paper plot of maximum daily gross vehicle weights, with fitted Weibull distributions, for standard and permit trucks at the Netherlands (NL) and Arizona (AZ) WIM sites.

3. Simulating truck traffic

Monte Carlo simulation of traffic is a well-established method for the estimation of probable lifetime maximum (characteristic) bridge loading (Bailey & Bez 1999; Enright & OBrien 2013; O'Connor & OBrien 2005; Nowak & Szerszen 1998), and is the approach adopted here. The aim is to simulate traffic which produces the same load effect distribution as the measured data while also simulating trucks which are heavier and have more axles than those in the measured data. A simulation model is developed here which is focused particularly on the accurate representation of permit trucks. The model is similar to the one described by Enright and OBrien (2012) which classified vehicles according to the number of axles, but did not differentiate between permit and standard trucks.

With ever greater quantities of WIM data becoming available worldwide (Fu & You 2011; Nowak & Rakoczy 2012; Walker & Cebon 2012) a more complete distribution of vehicle characteristics can be obtained. The datasets recorded at each of the WIM sites used in this work contain hundreds of thousands, and in some cases millions, of standard trucks. In the simulation, if a vehicle being generated is a standard truck (based on the proportion of standard trucks in the measured data), its characteristics (GVW, axles etc.) are determined by randomly selecting a standard truck from the measured data. This simple bootstrapping process is very efficient and is considered sufficient for the modelling of standard trucks because they do not tend to govern characteristic bridge load effects – as illustrated in Figure 3. Permit trucks, which are critically important in extreme loading events, require a more advanced simulation model due to the relatively small number of them in the measured data (typically less than 2%). Each new permit truck in the simulation is generated based on distributions fitted to the measured population of permit trucks, as described in the following sections. The four different types of permit truck – low loaders, mobile cranes, mobile cranes with dollies and crane ballast trucks – are treated separately.

3.1 Gross vehicle weight and number of axles for permit trucks

For each of the four vehicle types, the tail of a bivariate normal distribution is fitted to the measured GVW and number of axles using truncated maximum likelihood estimation (Enright & OBrien 2013). It is fitted to the top 100 trucks at each site in the case of the low loaders and the crane ballast trucks and to the top 50 for the mobile cranes and mobile cranes with dollies, as there tend to be a small number of these in the truck population at some sites. The distribution is fitted only to the tail as the aim is to capture the trend in the tail rather than the whole of the permit population, which includes unloaded and lightly loaded permit vehicles. The bivariate normal distribution allows trucks with larger GVW and number of axles than the measured data to be simulated. When simulating a permit truck, a combination of GVW and number of axles are randomly selected from the fitted distribution. Figure 4 shows a contour plot of the fitted distribution for low loaders at the Czech Republic site. The small quantity of data affects the quality of the fit but this is a necessary compromise in any tail-fitting process.

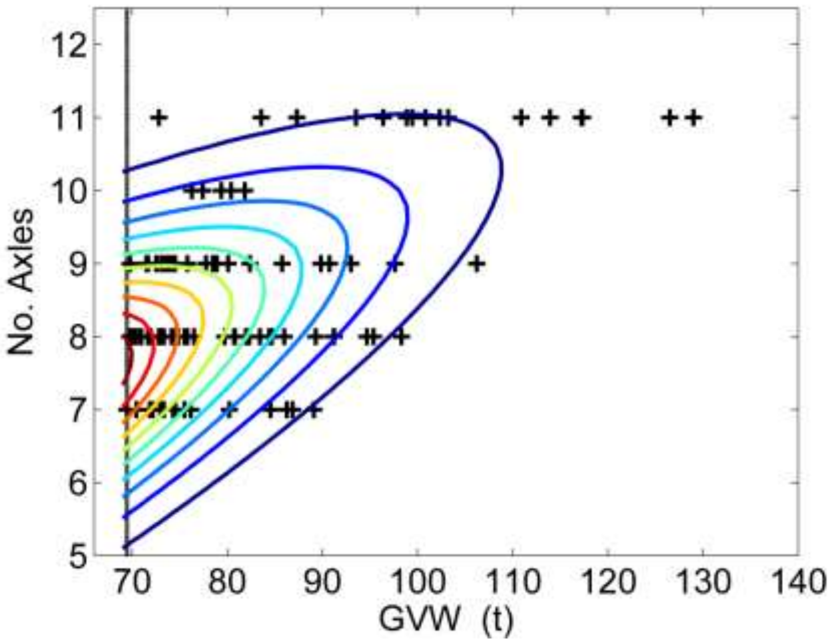


Figure 4. Measured data for low loaders at the Czech Republic site with contour plot of fitted bivariate normal distribution.

3.2 Inter-axle spacings and weight distribution

In the simulation, the inter-axle spacings and weight distribution are generated in different ways for each type of permit truck, based on the characteristics found in the measured data for each type. The approach used here is summarised in Figure 5. Mobile cranes with dollies are not simulated in Europe, as they are not found in this region, and similarly crane ballast trucks are not simulated in the US.

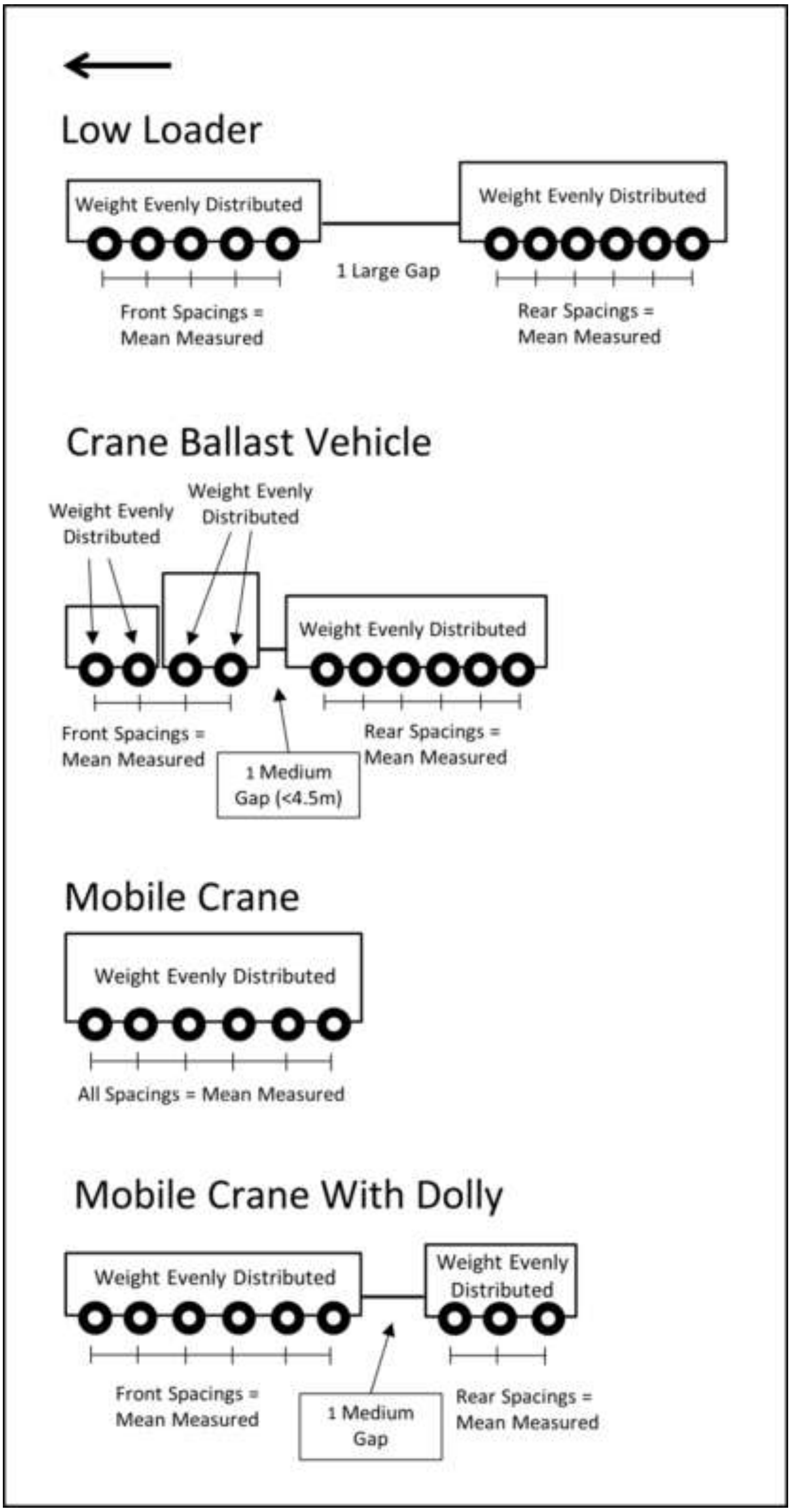
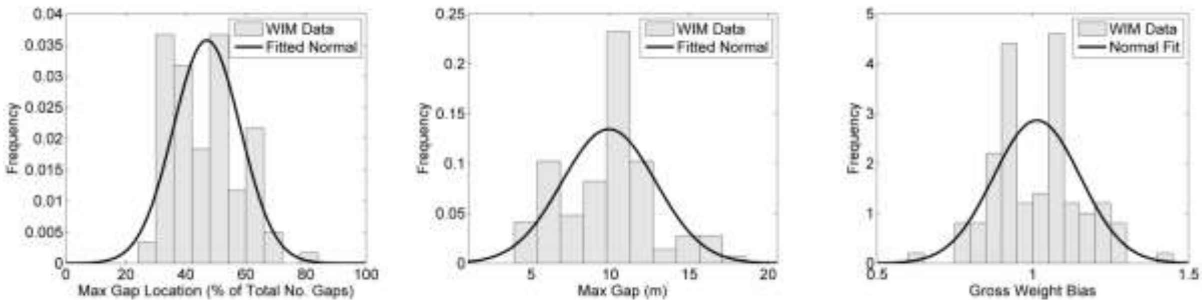


Figure 5. The four types of permit vehicles generated by the simulation model.

Mobile cranes are the simplest to simulate as they have similar axle spacing and a relatively uniform distribution of the GVW between the axles. When generating a mobile crane, all axle spacings are made equal to the average measured axle spacing for these vehicles. The selected GVW is then evenly distributed between the axles. A more complex approach is not needed as it was found that this method simulated load effects which matched well those produced by the WIM data.

The key determinants of the axle configuration of low loaders are the location and magnitude of the maximum axle spacing and the proportion of the GVW before and after that maximum spacing. The magnitude of the maximum axle spacing in particular, can have a significant effect on the resulting load effects, especially the hogging bending moment over an internal support of a continuous bridge. Normal distributions are fitted to the measured data for these properties – see Figure 6. These distributions allow the simulation of axle configurations and weight distributions which were not observed during the WIM measuring period. This is important as all possible configurations for these infrequent trucks will not be observed in a limited measuring period. During the simulation process, values are then randomly selected from these distributions in order to generate axle configurations and weight distributions which may be different to the measured data but which match the observed trend.



(a) Location of the maximum axle spacing.

(b) Magnitude of maximum axle spacing (restricted to a minimum of 4.5 m).

(c) Bias of GVW towards front of truck.

Figure 6. Histograms of low loader characteristics at Czech Republic site with fitted normal distributions.

The low loader generation process also allows for a bias of weight towards the front or back of the low loader. The bias is calculated as the ratio of the portion of the GVW before to that after the maximum spacing. A Normal distribution is fitted to the measured bias data and this is then used to distribute the weight for each simulated vehicle. The weight within each portion is then evenly distributed between its axles. The axle spacing before and after the maximum spacing are set at the mean measured values for each group. Mobile cranes with dollies have a similar axle configuration to low loaders and are simulated in a similar way.

Crane ballast vehicles are simulated in a similar way to low loaders but with the addition of an extra parameter. On these vehicles the pair of axles immediately before the maximum spacing is found to be significantly heavier than the other axles in front of this pair. To allow for this, a second normal distribution is fitted to the bias in weight of these two axles relative to the total weight before the maximum spacing.

3.3 Simulating a continuous stream of traffic

Once individual vehicles have been defined, a stream of traffic is then simulated by modelling inter-vehicle gaps according to the hourly traffic flow rate at each site. The method used is similar to that described in (OBrien & Caprani 2005; Enright & OBrien 2013)

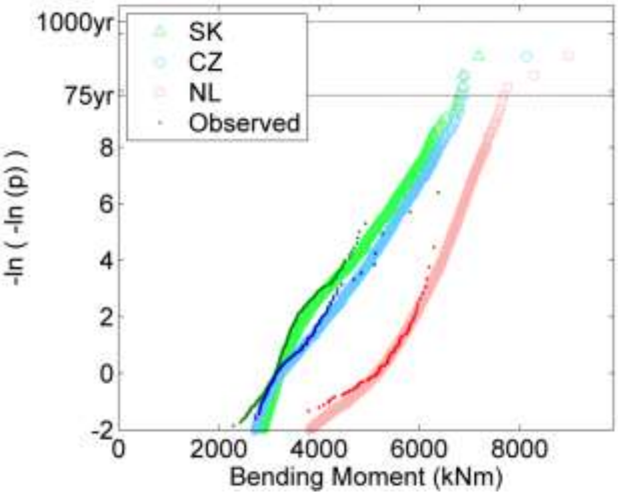
Examination of the WIM data at different sites shows that there is a tendency for permit trucks to travel in convoys. At the Netherlands WIM site 6.1% of permit trucks are followed by another permit truck. This figure is 3.1 times greater than if the order of trucks were completely random. This increases the likelihood of permit-following-permit bridge loading events. The simulation algorithm takes this into account and simulates permit–following-permit events at the same rate as the measured WIM data.

For each simulated day of traffic the maximum daily load effects are calculated. The load effects examined are mid-span bending moment on a simply supported bridge (LE1), shear at a support on a simply supported bridge (LE2) and hogging moment over the central support of a two-span continuous bridge (LE3). These load effects are calculated for total bridge lengths of 20, 30, 40 and 50 m by passing the simulated traffic over the relevant influence line for simple beam models.

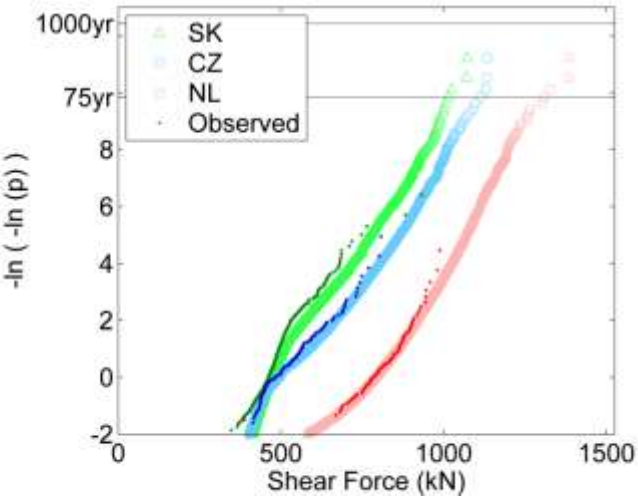
3.4 Model validation

To validate the model simulations are performed for three of the European WIM sites – Netherlands, Czech Republic and Slovakia – and for three of the US sites – Arizona, Illinois and Indiana. Traffic flows at these six sites range from 1,000 to over 6,000 trucks per day in one direction. Traffic is simulated as a single lane in one direction. The accuracy of the load effects produced by the model is assessed by plotting the maximum daily observed and simulated load effects, for all vehicles (both standard and permit) in Figure 7. For clarity, the two truck types are not plotted separately here.

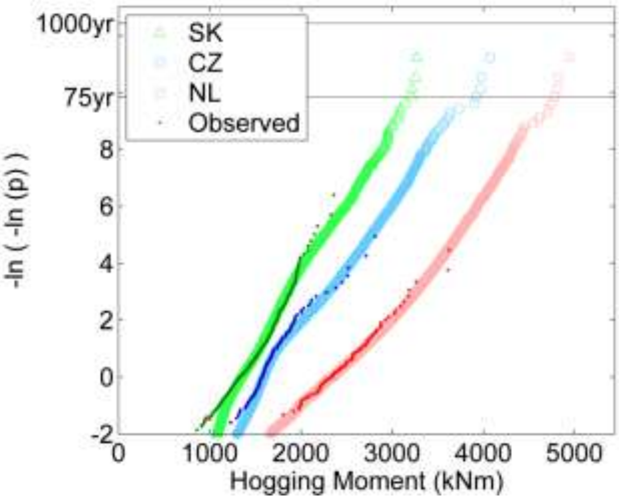
This validation process has been done for all load effects and span lengths in both Europe and the US and a representative sample of these plots is shown in Figure 7. The trends are straight or curved slightly upwards on Gumbel probability paper, suggesting compliance with the Weibull distribution. Good fits are achieved in all cases, confirming the validity of the long run simulations. In Figure 7(c), the upper tail of the simulated Illinois moments do not sit over the measured data as the simulation smooths the random variation in the observed data.



(a) LE1 on a 30 m bridge.



(b) LE2 on a 40 m bridge.



(c) LE3 on a 50 m bridge.

Figure 7. Observed vs. simulated maximum daily load effects for the three European WIM sites. All simulations represent 300 years of traffic (SK = Slovakia, CZ = Czech Republic, NL = Netherlands).

4. Conclusion

The ability to identify permit trucks in WIM data is critically important for site-specific assessment of bridge loading, developing load models for bridge design/assessment and examining weight enforcement, illegal overloading and permitting policy. Rules are developed for identifying the different permit truck types in European and US WIM data. The rules identify these trucks based on their axle configuration. The data is separated into two categories - apparent standard and apparent permit - which have distinctly different statistical properties. It is shown that the apparent permit truck category is the critical group for bridge loading.

A traffic simulation model for bridge loading is also developed which allows the accurate simulation of the different types of European and US permit trucks which are critical for bridge loading. The model uses simplified axle configurations to simulate these trucks. The ability to model permit trucks independently of standard trucks is important for the estimation of maximum lifetime bridge traffic loading, as both truck types are regulated in different ways and need to be analysed separately.

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